SEARCHING FOR DARK MATTER IN NEUTRINO BEAMS

by

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Abstract

SEARCHING FOR DARK MATTER IN NEUTRINO BEAMS

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Dark Matter detection is currently a major area of interest for research. For the past 45 years many ideas and experiments have been investigated to explain the existence of and to detect Dark Matter. Since these experiments have yet to yield any wholly affirmative results it may be time to look for other ways to detect Dark Matter. This particular study looks at the possibilities for Dark Matter detection in neutrino beams at the Deep Underground Neutrino Experiment (DUNE). Simulations for specific parameters were run using MadGraph5 and the results for those data runs are presented and discussed. Areas of future necessary study are mentioned and ranges of possible Dark Matter masses and their effects on detection prospects are included. The initial results seem to bode well for the future of Dark Matter detection at DUNE.

Table of Contents

List of Illustrations

Chapter 1

Introduction

Dark Matter is a phrase that many people are familiar with regardless of their academic background. The term has been around longer than most of the researchers who are currently trying to detect it. So why has it taken so long to detect this Dark Matter even though its effects are so pronounced? The ideas, methods, and techniques for trying to detect Dark Matter are numerous and while some have been dismissed altogether some are still ongoing. But since nothing has yet to come from these still ongoing experiments perhaps it is a good idea to expand the way searches for Dark Matter are currently done. There is a new experiment in the works called the Deep Underground Neutrino Experiment that could do just that. While its main goal is to produce a neutrino beam through protons hitting a fixed target it is thought that Dark Matter could also be produced from this experiment. The illustration in Figure 1-1 shows this idea that the neutrinos lead the pack of particles created in these experiments but they are not alone.

Figure 1-1 Neutrino Beam Production Creates Some Additional Particles (3)

Chapter 2

The Story of Dark Matter

The first astronomical observations of Dark Matter can be traced back to the 1930's with the work of Fritz Zwicky. Zwicky was an astronomer who noticed some anomalies while studying the Coma Cluster. He determined that there was not enough visible matter in that cluster to account for the speed of the material found within the Coma Cluster. So he coined the term "Dark Matter" since he knew something was there causing those effects even though he could not see it. Zwicky's work remained wholly ignored for forty years until the work of Vera Rubin and others in the 1970's. Rubin's work on galaxy rotation curves brought about the discovery that there existed a divergence between the observed and predicted speeds of material at the outer edges of galaxies. Based on all the visible material and Newtonian mechanics it would be expected that the orbital speed of material at the outer edges of galaxies would decrease, much like what is seen on a planetary scale. Instead Rubin found that the orbital speeds do not drop off, they flatten out to stay constant and in some instances the orbital speeds increase. This is illustrated in Figure 2-1. The image and data represent Messier 33 (M33), the Triangulum Galaxy. This local group galaxy had data collected for orbital rotation velocities from various points starting with the innermost region and outward using direct starlight and 21 cm hydrogen lines for more obscured stars. The figure clearly shows what the orbital speeds should be for M33 based on Newtonian mechanics with the dashed line but the solid line shows what is actually observed. Material at the outer edges shows no signs of slowing down but in fact speeds up! This is just one of many cases of galaxies that do not follow the expected rotation curve for the observed data in galaxies. For all the observed data to make sense for all these cases there must be more material in galaxies to make them more massive than they appear to be, which again points to the unseen Dark Matter.

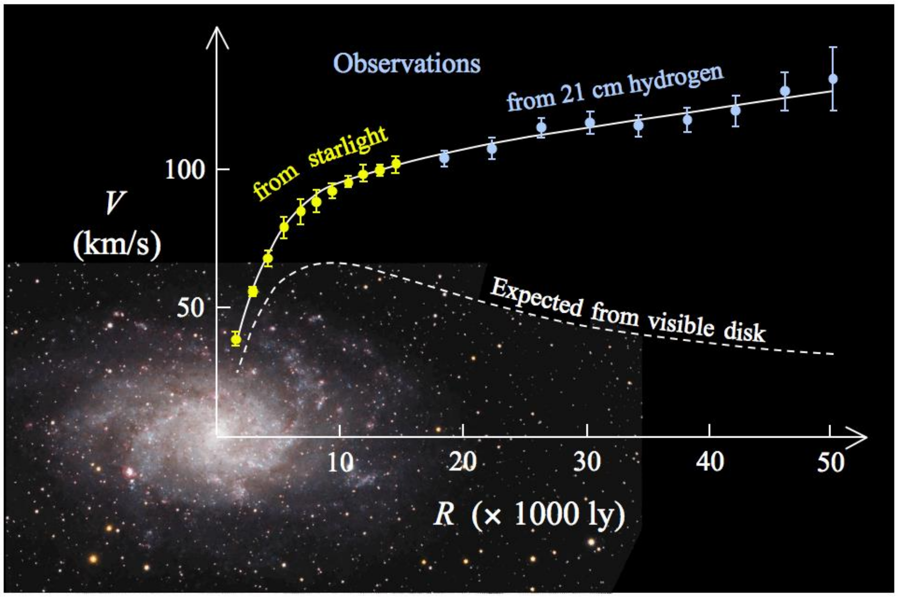


Figure 2-1 Rotation Curve (4)

With the several cases of observational data and overall acceptance of its existence, what are the possible candidates for Dark Matter (DM)? There has been discussion of Massive Compact Halo Objects, referred to as MACHOs, as possible candidates for DM. MACHOs are objects that would be hard to detect, like neutron stars, black holes, brown dwarfs, and white dwarfs, that could be located out in the haloes of galaxies. It is now widely believed that MACHOs do not make a good sole candidate for DM since there is no plausible way for enough of the objects to accrue in haloes to account for the effects of DM. This is known because the amount of MACHOs needed to account for all DM would be easily detectible through methods such as gravitational lensing. Another candidate introduced was Modified Newtonian Dynamics, also known as MOND. MOND suggested that Newton’s laws needed to be modified in order to explain the observed rotation curves of galaxies. While MOND did an excellent job of recreating and fitting to much singular galactic phenomena it breaks down when dealing with galactic clusters, most famously the Bullet Cluster observations. Figure 2-2 is a composite image of the Bullet Cluster of galaxies. Observationally, there is not enough material to account for the motions seen as these galaxies interact with each other. The red in the figure is the collective hot x-ray emitting gas whereas the blue show the distribution of DM in the cluster, which was determined by the observation of gravitational lensing. The DM has passed through this collection of hot x-ray emitting gas instead of being mixed within the same region creating the two blue lobes. Since MOND does not work to explain the motions of galactic clusters, it must be set aside as a candidate for DM.

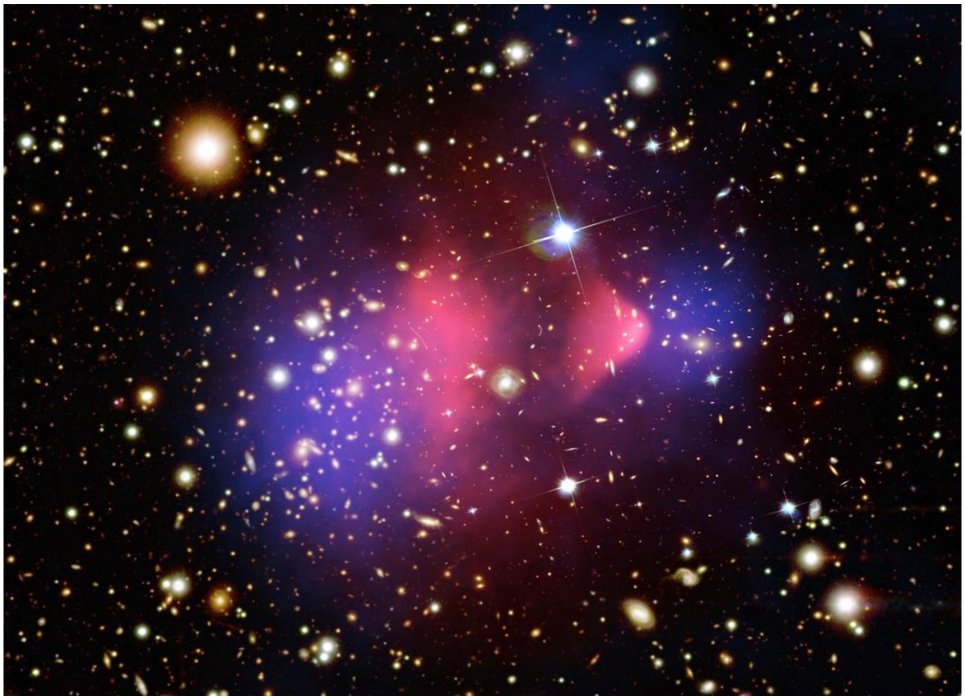


Figure 2-2 The Bullet Cluster (5)

Now what about Standard Model particles? The Standard Model consists of the electromagnetic, weak, and strong nuclear forces that are the classification of all the know elementary particles but are not currently unified. The known elementary particles are fermions consisting of six quarks and six leptons, gauge bosons consisting of a photon, W^+, W^-, and Z, and 8 gluons, and finally the Higgs boson. Figure 2-3 categorizes all these particles in a concise and informative infographic.

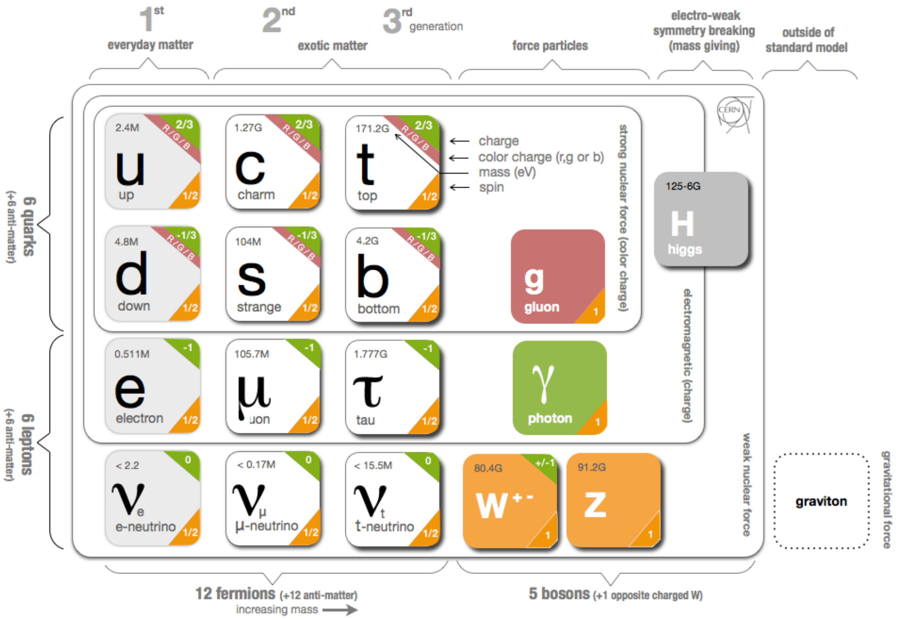


Figure 2-3 Standard Model (6)

What is known about the current structure of the universe means that what is being looked for must be non-relativistic therefore the majority of DM must be Cold (1). Cold DM works to agree with observational large scale structures though the use of computer simulations to compare against the known structure of the Universe but falter at smaller scales like dwarf galaxies (1). This directs one to look outside the Standard Model for other possibilities. A good place to investigate is Weakly Interacting Massive Particles (WIMPs). Based on current models of the universe particles with weak scale masses on the order of 100’s GeV can correctly predict the amount of DM that is present now. So how does one go about detecting these WIMPs? There are several methods of direct detection, indirect detection, and direct production.

For the direct detection approach energy signatures are stored by a detector from the DM particles found within the Milky Way Galaxy as the Earth moves through the halo (1). This method is sensitive to the very subdominant WIMP piece of the DM (1). There are many current and future direct DM detection experiments using various target materials and detection approaches. The experiments DAMA/LIBRA, CoGeNT, and CDMS-II-Si are all direct detection experiments that have claims of observed potential DM signals (1). Figure 2-4 shows those experiments which have claimed potential DM signals by encircling the region. All the other direct detection experiments like LUX, XENON100, CDMS-II-Ge, CDMAlite, SuperCDMS, and more have only been able to produce upper bounds on the interaction rate and annual modulation amplitude of a potential WIMP signature (1). This is shown by the boomerang shaped boundary lines in Figure 2-4. Since these experiments are more sensitive they exclude and dismiss the likelihood for the previous potential DM signals validity.

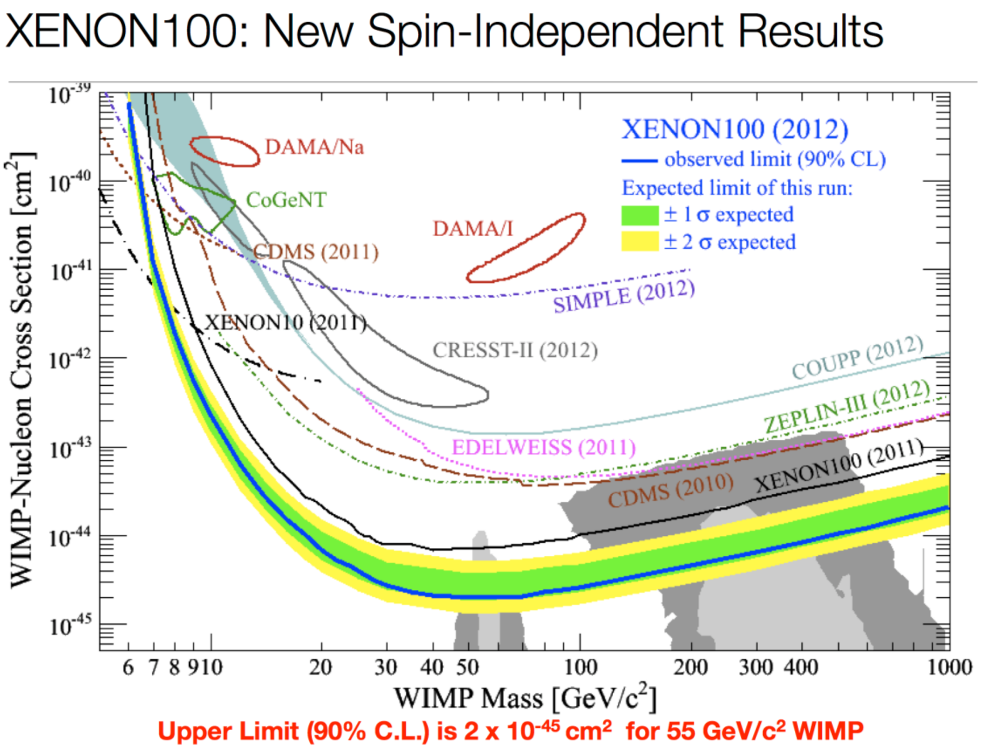


Figure 2-4 WIMP Direct Detection Results and Boundaries (7)

For the indirect detection approach DM annihilation or decay products are searched for as high energy neutrinos produced by WIMPs captured inside the Sun or Earth (1). These could be anomalous cosmic rays such as photons, gamma rays, neutrinos, and Standard Model particle and anti-particle pairs like positrons and anti-positrons, which do not come from astrophysical sources (1). Experiments that are indirect detection work on the premise that as the Sun and Earth move through the halo of the Milky Way galaxy, WIMPs can occasionally scatter with the baryonic matter in one of these bodies and lose enough energy to become gravitationally bound to that body (1). Annihilation products in the form of neutrinos are able to escape from the Sun or Earth and can be differentiated from the neutrinos produced by the bodies by their significantly larger energies (1). Figure 2-5 show an example of DM WIMPs captured by the Sun where annihilation occurs and the resulting neutrino escapes in the direction of Earth where it encounters a detector. Current experiments using indirect detection for DM are EGRET, Fermi Gamma-ray Space Telescope, PAMELA, IceCube, and ANTARES but have thus far been unable to conclusively determine any DM signals.

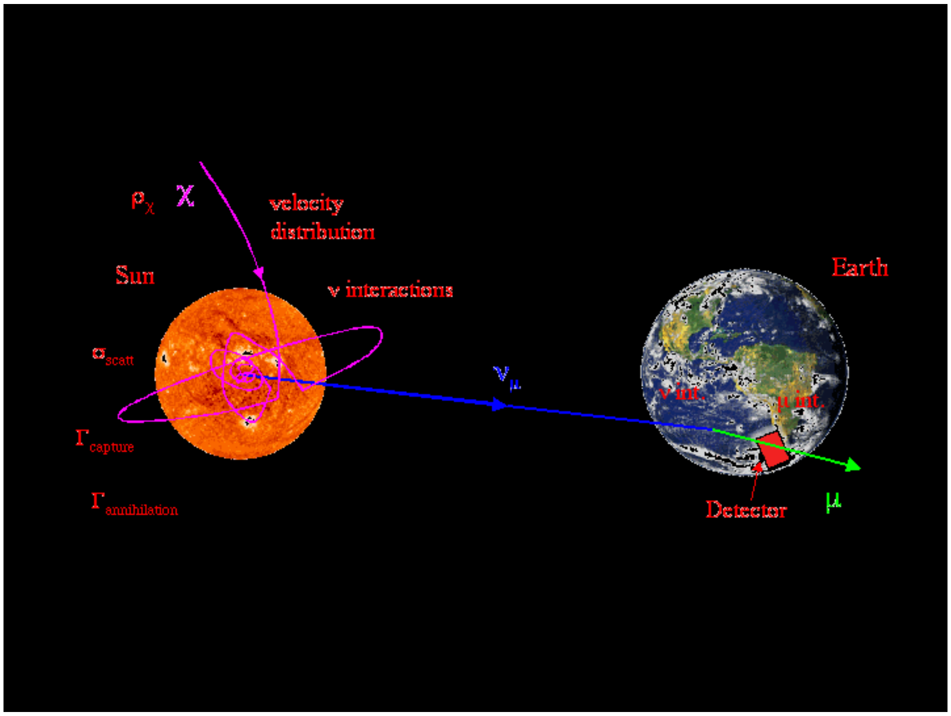


Figure 2-5 WIMP Indirect Detection Scenario (8)

The direct production route works under the idea that DM particles can be produced through proton-proton collisions, much like what occurs at the Large Hadron Collider (LHC) in Geneva, Switzerland. This utilizes the fundamental equation $E = mc^2$ where the experiment puts energy, E, in so that DM mass, m, will come out on the other side and be detectable. This search has been underway for some time and is still ongoing but there has been nothing substantial yet so perhaps it is time to look elsewhere. For the handful of years that direct detection, indirect detection, and direct production have been underway it would behoove the greater scientific community to think of alternative methods and experiments to search for DM particles. One such idea that has come about is Dark Matter detection at fixed target experiments.

Chapter 3

Dark Matter at Fixed Target Experiments

The focus of this research is on the detection of DM at fixed target experiments, like what could be conducted at the Deep Underground Neutrino Experiment, DUNE (formerly the Long-Baseline Neutrino Experiment, LBNE). Low-energy, fixed target neutrino beam experiments have been gaining interest as a method to detect DM (2). Unlike previously mentioned direct detection and collider experiments, these neutrino beam experiments have been shown to provide excellent coverage of the DM and mediator parameter space (2). In order to explain how light DM would be produced at a neutrino beam experiment it is important to explain how the neutrino beam experiment works. For neutrino production, these types of experiments usually involve a proton beam hitting a target of varying material (based on whatever the experiment chooses to use) (2). Mainly charged pions are produced from these collisions where the pions promptly decay into muons and neutrinos with the eventual decay of the muons providing further neutrinos (2). This is shown as the black text series of decays in Figure 3-1.

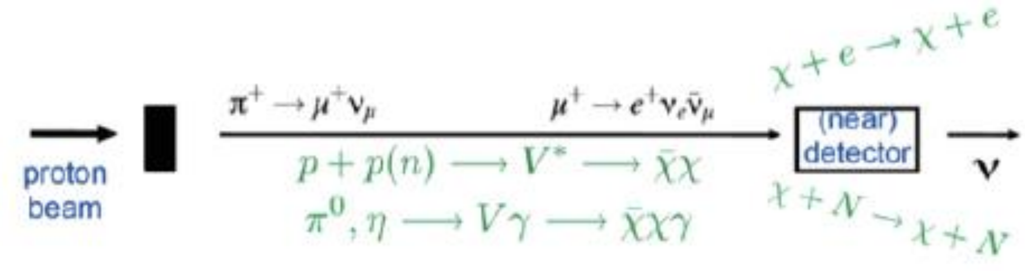


Figure 3-1 Neutrino and Dark Matter Creation Scenario (2)

The production of the light DM particles could come from varying forms of decay processes and the green text series of decays in Figure 3-1 shows some possible events. For this case the DM particles would come from the first step of pion creation after the proton beam interaction with the target (2). The collision produces charged pions as well as neutral pions (eta mesons), which in the Standard Model decay nearly one hundred percent of the time into two photons (2). Yet a small fraction of the neutral pions (eta mesons) could decay into one Standard Model photon and one dark photon if the Standard Model U(1) gauge field mixes with an extra U(1) gauge field (2). Figure 3-2 shows the Feynman diagram for this case.

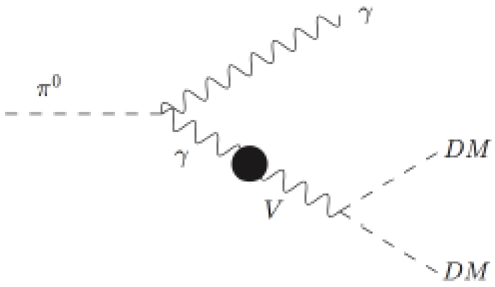


Figure 3-2 Neutral Pion Decay DM Production (2)

This dark photon would then rapidly decay into two DM particles with the assumption that the dark photon mass is at least twice the mass of the DM particle (2). DM particle could also be produced more directly by means of on-shell production of V through the partonic process qq/bar→V with the ensuing decay of V into two DM particles (2). Figure 3-3 shows the Feynman diagram for this process.

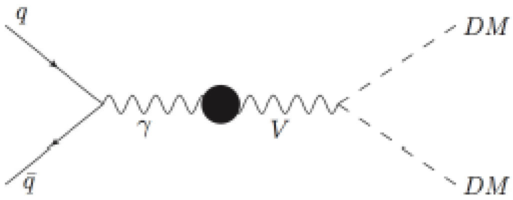


Figure 3-3 DM Production through On-Shell Production of the Dark Photon (2)

In each case, the cross section for the production of DM particles in proton-target collisions is fairly small due to the weak interactions and mixing parameters involved (2). The extremely large intensities at these particular proton-target interaction experiments can easily make up for that shortcoming (2). The end result is a beam of relativistic DM particles that propagate down the beam pipe alongside the neutrinos. The DM particles in the neutrino beam can be detected with a near detector via neutral-current like interactions with either electrons, which Figure 3-4 shows the Feynman diagram for this case, nucleons or nuclei in the detector (2).

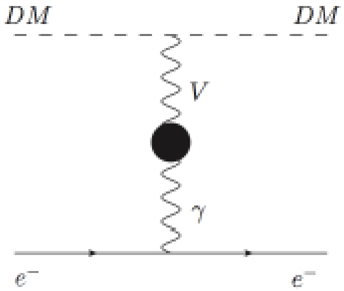
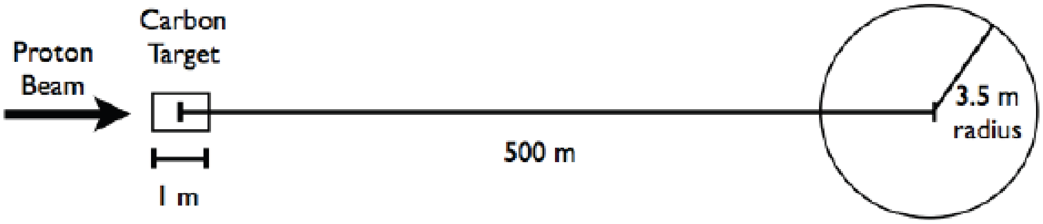


Figure 3-4 DM Detection through Scattering of Electrons (2)

At a beam energy of 120 GeV the direct production process will dominate. There are some past and current neutrino beam experiments but this work will focus on the future work to be conducted by DUNE. DUNE is located outside of Fermilab in Illinois and the far detector for neutrinos is housed in South Dakota about 800 miles away. The near detector where DM detection is more feasible would be much closer to the site at Fermilab though the exact location has not yet been determined. In order to determine how and where the experiment for DM detection should be laid out there were simulations to be carried out to see what could be possible. One million DM production events were generated using the program MadGraph5 in Fixed Target Mode. Since some of the parameters are not set yet, like the size and distance of the near detector, the chosen initial parameters are still flexible. These simulation parameters are laid out in Figure 3-6 and were used to for the one million DM production events. All results come from these set initial parameters



$N_{POT} = 3 \times 10^{21}$ (number of protons on target)

$n_T = 10^{23}$ (number density of carbon atoms in the target)

$L_T = 100$ cm (length of target)

$\text{Theta}_{det} = 3.5\text{m}/500\text{m} = 0.007 = 0.4$ degrees (angular acceptance)

$n_D = 5 \times 10^{23}$ (number density of electrons in detector)

$R_D = 350$ cm (radius of detector)

$d = 500$ m (distance from target to detector)

Figure 3-5 Simulation Parameters (3)

Chapter 4

Results

The results of these simulations will allow for a better understanding of the best way to set up DUNE what results might occur when DUNE is underway. Figure 4-1 shows the energy distribution of the accepted DM and neutrinos. Accepted DM and neutrinos mean the particles that will actually hit the near detector. It is easy to see that the neutrino signal in blue completely swamps out the DM signal in red. Since neutrinos interact with the detector material in the same way as the DM it was thought that neutrinos would make up an overwhelming background to the DM, which Figure 4-1 shows this to be the case (2).

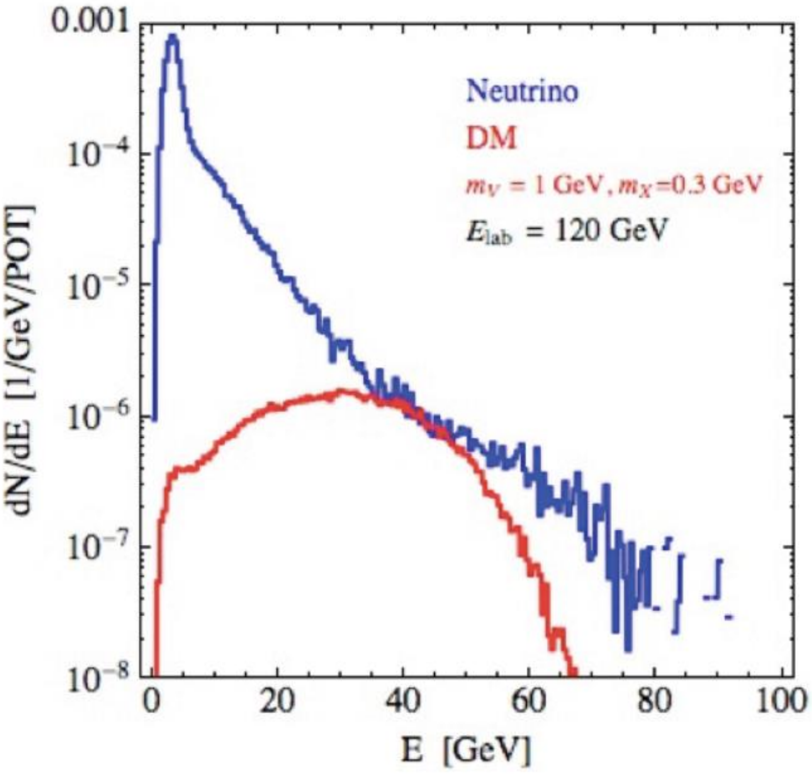


Figure 4-1 Energy Distribution for Dark Matter and Neutrinos

Understanding this will allow for future dedicated studies to be commissioned so that precise accounts for beam fluxes of both DM and neutrinos can be determined plus more thorough studies on detector performance (2). One idea is to have a cut off limit on the near detector in energy ranges where neutrinos dominate, which based off figure 4-1 would certainly include the range of 0 to 30 GeV. Figure 4-2 shows the angular distribution of particles that hit the detector with the neutrino background as the solid black line and the DM particles as the dashed line.

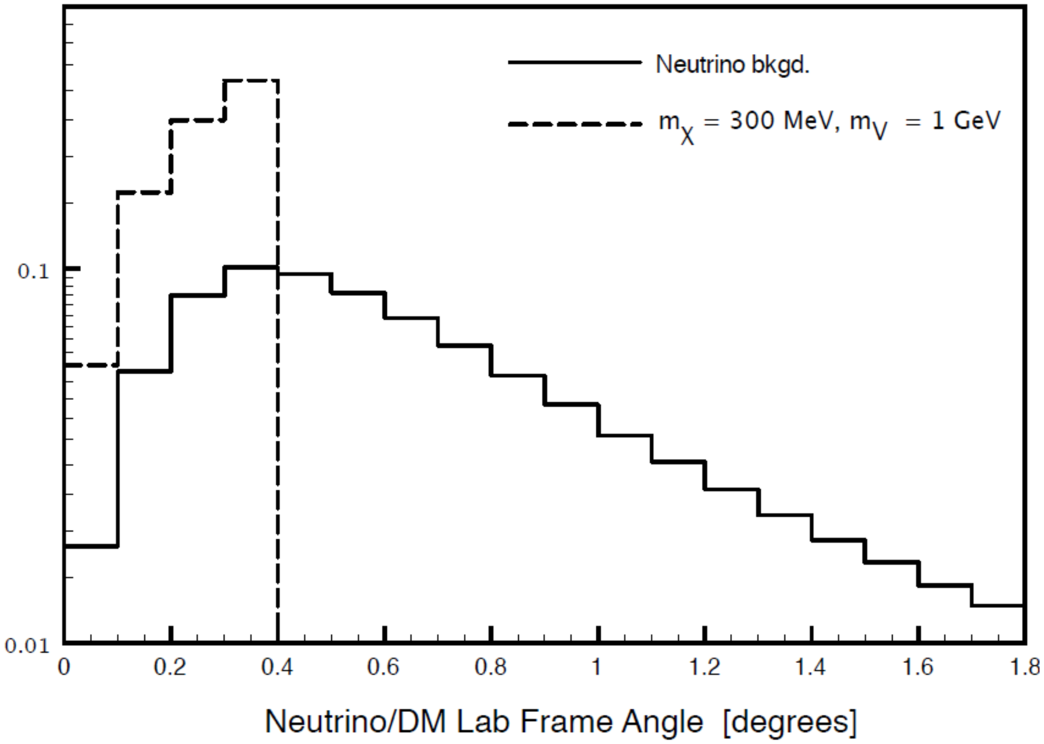


Figure 4-2 Angular Distribution for Dark Matter and Neutrinos

The DM and neutrino curves differ so much due to the location of their particle productions. Neutrinos production occurs further down the beam line after it hits the target but DM is produced directly at the target so by the time the particles reach the near detector, remember our simulation has it set 500 meters away, the DM particles have had ample time travel and spread far out. This simulation shows that only DM particles that leave the target at an angle of less than 0.4 degrees will be detectable. Knowing this allows for better understanding of what might be an improved design or location of the near detector since those parameters have not yet been determined. Figure 4-3 is an example of what the experimentalist will actually be measuring when this experiment gets underway, the scattered electron energy. This graph shows two possibilities for the mass of DM, 300 MeV in blue and 1 GeV in red, to compare to the neutrino background.

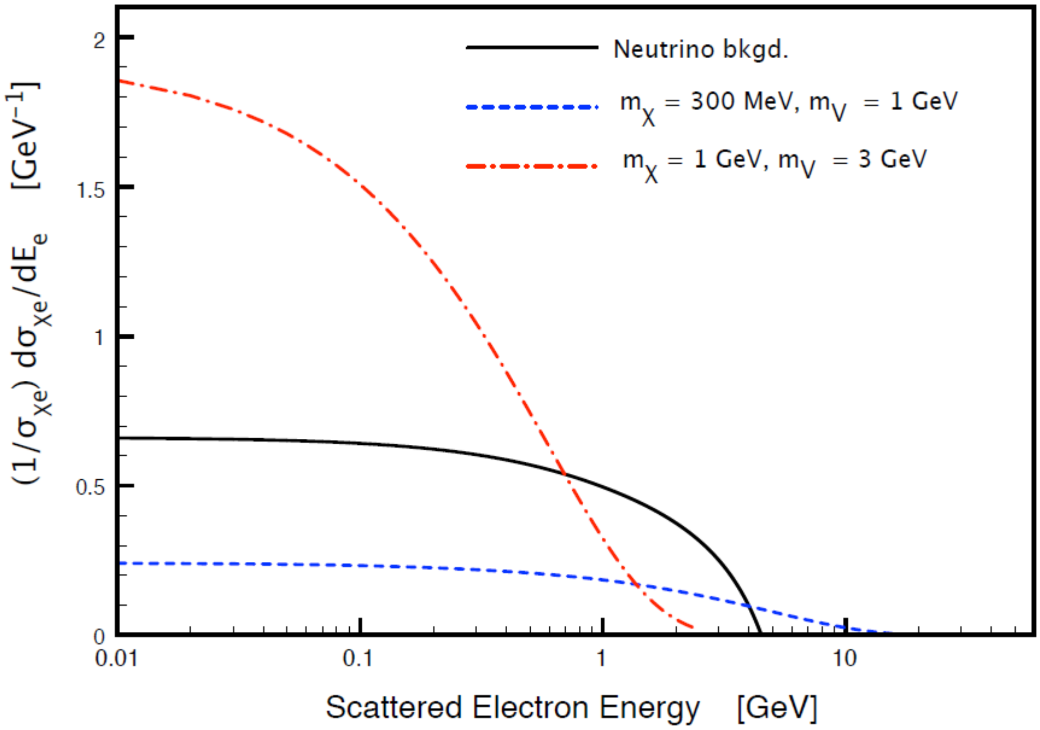


Figure 4-3 Scattered Electron Energy for Dark Matter and Neutrinos

It is important to notice that if the DM particles are relatively light they will be completely overshadowed by the neutrino background. The DM electron scattering channel will only be a good observable case if DM is relatively heavy, like 1 GeV. It is important to know the limits an experiment is viable at since the mass of DM is not yet clearly defined. This can also be seen with Figure 4-4. It shows the angular distribution of the scattered electrons, which leads to the same conclusions as before. It is almost impossible to discern relatively light DM particles in blue from the neutrino background as they overlap almost perfectly.

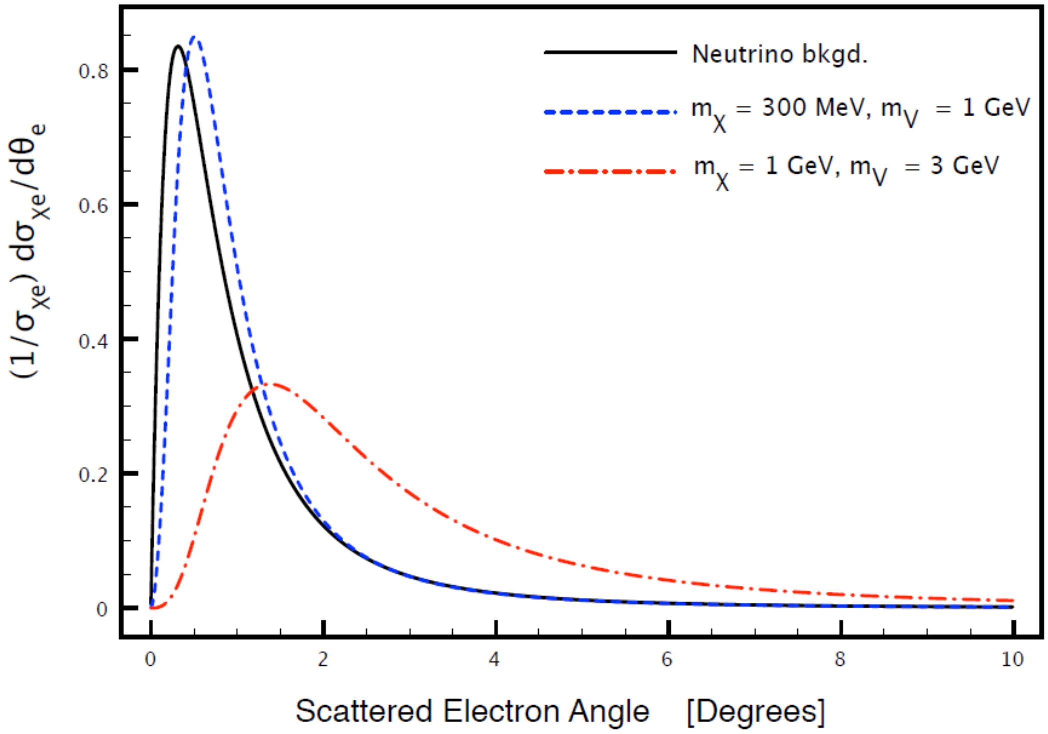


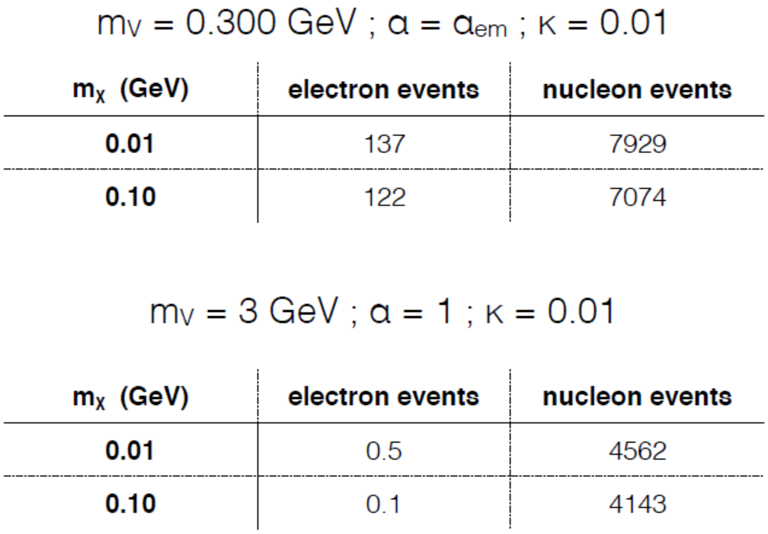
Figure 4-4 Scattered Electron Angle for Dark Matter and Neutrinos

It is hoped that DM would be relatively heavier since the red curve has a much more distinct and independent shape from the neutrino background. With all this information laid out, how many DM particles could be detected? Figure 4-5 gives the equation used for the number of events.

$$N_{\text{event}} = N_{POT} \times n_T\, L_T \times (12\sigma_{pp(n)\to\chi\bar{\chi}}) \times n_D\, R_D \times \sigma_{\chi e(\chi N)} \times \eta_D \times \epsilon_D$$

Figure 4-5 Event Number Equation (3)

The η_D acceptance is set at 0.042%, the ϵ_D efficiency is set at 50%, and the electron and nucleon scattering cross sections are roughly $\sigma_{pp\to\chi\chi/bar} \approx 10^7$ pb = 10^{-29} cm^2 from madgraph and $\sigma_{\chi e(\chi N)} \approx 10^{-32}$ cm^2 found analytically. Using these values plus the original parameters laid out in Figure 3-6 the number of events is found to be $N_{event} \approx 10^{10} \times \kappa^4 (\alpha_D/0.1)^2$. This means for even conservative choices of couplings there could be 100's to 1000's of events to detect. Figure 4-6 shows some example electron scattering and nucleon scattering events for some varying parameters such as DM and neutrino mass.



$m_V = 0.300$ GeV ; $\alpha = \alpha_{em}$; $\kappa = 0.01$

m_χ (GeV)	electron events	nucleon events
0.01	137	7929
0.10	122	7074

$m_V = 3$ GeV ; $\alpha = 1$; $\kappa = 0.01$

m_χ (GeV)	electron events	nucleon events
0.01	0.5	4562
0.10	0.1	4143

Figure 4-6 Electron and Nucleon Scattering Events (3)

As before it is easy to see that not only will relatively heavier DM particles bring about more scattering events but nucleon scattering events would provide more data than electron scattering events. Overall much can be determined from these simulations about the future of DUNE. It allows for informative investigation on optimal design and set up of the near detector and the best and worst case scenarios for many possible aspects of DM.

Chapter 5

Conclusions

For the past 45 years much work has been done towards trying to discover what actually makes up the hard to detect Dark Matter. Though Zwicky's work on Dark Matter prior to the 1970's was completely ignored it is now a hot topic in current scientific research with such a widespread popularity that most people have heard of the term Dark Matter. Tons of ideas on how to detect this illusive matter exist using what is known from astronomical observations, fundamental physics properties, the Standard Model of particles to finally looking outside of all that in order to detect something new. And with that came searching for these new particles called Weakly Interacting Massive Particles using several methods of direct, indirect, and direct production methods but there is still no real proof of what makes up Dark Matter. So the world must push on to new ideas, which leads to the Deep Underground Neutrino Experiment and its possibility for Dark Matter production thought a fixed target experiment. The Deep Underground Neutrino Experiment presents possible exciting options for the detection and study of sub-GeV Dark Matter during these early stages of development. The results from simulations have shown that the current estimated signal rates look promising. Detection through electron scattering could be more difficult but nucleon scattering should lead to larger cross sections and scattering rates. One of the most important factors for the success of this experiment is suppressing the neutrino background, which can be further studied and evaluated. Another area to be studied in more detail would be some of the parameters that have not yet been designated, such as the optimal location and dimensions of the near detector. A bigger and closer near detector would mean the possibility of more events, which would be ideal for any experiment. There is still much work to be done in order to optimize the potential DUNE would have to detect possible Dark Matter created through its neutrino beam experiment. The theoretical work done with these simulations helps to better prepare the experimentalists on perfecting the set up and design for such Dark Matter related experiments and hopefully this future collaboration with DUNE will be a fruitful one.

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Biographical Information

Crystal Nicole Chumani Red Eagle was the first in her family to obtain a Bachelor's and Master's degree and these achievements mean a great deal to her and her proud family. Her research as an undergraduate was wide ranging and included areas of Advanced Mathematics, Space Physics, Cosmology, and Physics Education. She was also afforded many great opportunities as an Astronomy Teaching Assistant, funding to attend and present research at many regional and national conferences, and various academic awards including University Scholar and McNair Scholar. After spending her final semester studying abroad in England at the University of Leicester she graduated cum laude with a major in Physics and a double minor in Mathematics and Classics. After taking some time off to teach she returned to academia to pursue her Master's degree in Physics. She decided to continue her undergraduate research interest in Dark Matter but from the High Energy Physics perspective. As she prepares to graduate with her Master's she is currently searching for jobs that will continually challenge and inspire her desire to learn while using all the skills she has acquired throughout her years devoted to Physics. She is eager to begin this exciting new chapter in her life.